BOUT++ simulations of H-mode pedestal of tokamak devices

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19-21 September,
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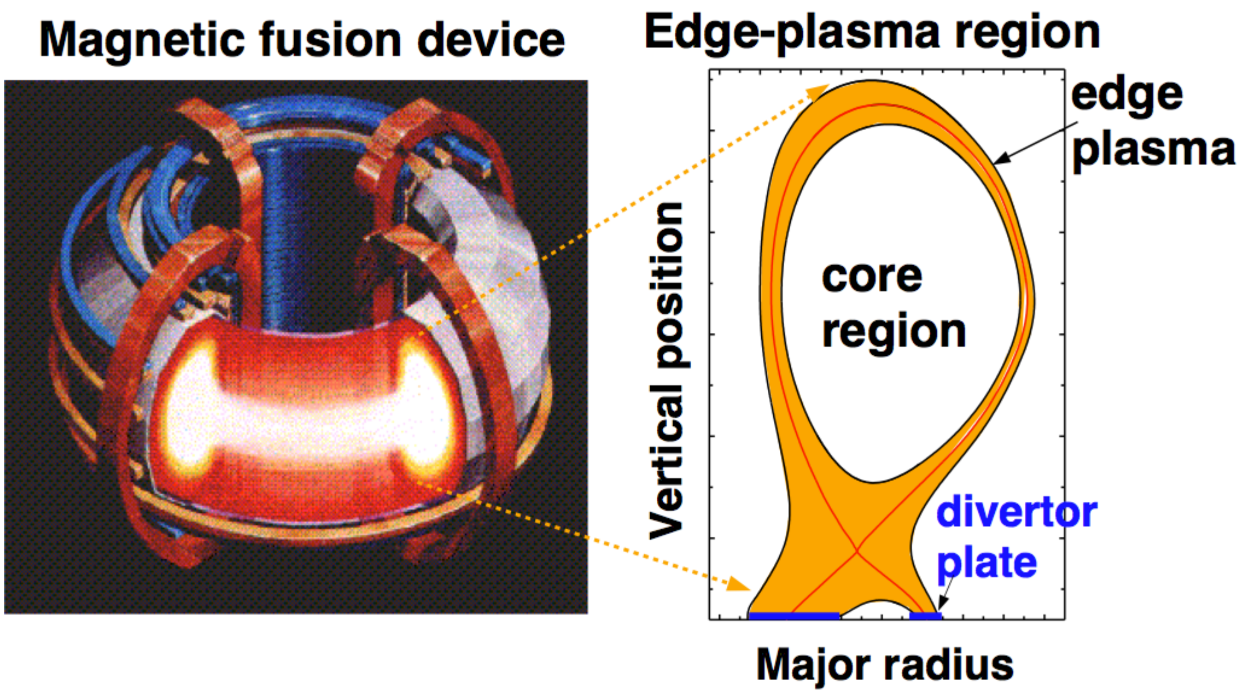
Tokamak edge region encompasses boundary layer between hot core plasma and material walls

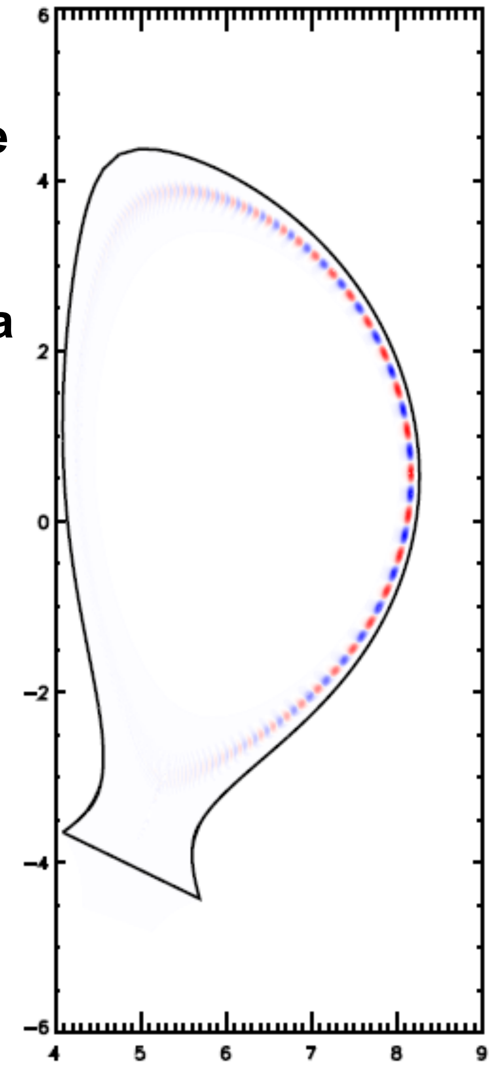
- Complex geometry
- Rich physics (plasma, atomic, material)

- Sets key engineering constraints for fusion reactor
- Sets global energy confinement



BOUT (BOUndary Turbulence) was originally developed at LLNL in late 1990s for modeling tokamak edge turbulence*

- **Boundary Plasma Turbulence has a different characters than in the core and play an important role in the core confinement**
- **BOUT is an unique code to simulate boundary plasma turbulence in a complex geometry**
  - **Observed large velocity shear layer**
  - **Proximity of open+closed flux surface**
  - **Presence of X-point**
- **BOUT/ BOUT++ codes has being applied to DIII-D, C-MOD,NSTX, MAST, ITER scenarios, ⋯**



**** X.Q. Xu and R.H. Cohen, Contrib. Plasma Phys. 38, 158 (1998)***
Xu, Umansky, Dudson & Snyder, CiCP, V. 4, 949-979 (2008).

BOUT++ is a successor to BOUT, developed in collaboration with Univ. York*

BOUT++
Boundary Plasma Turbulence Code

Original BOUT, tokamak applications on boundary turbulence and ELMs with encouraging results

BOUT-06: code refactoring using differential operator approach, high order FD, verification

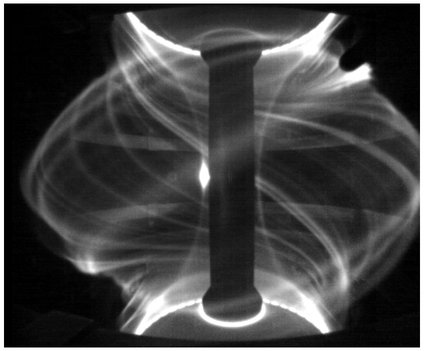
BOUT++: OOP, 2D parallelization, applications to tokamak ELMs and linear plasmas

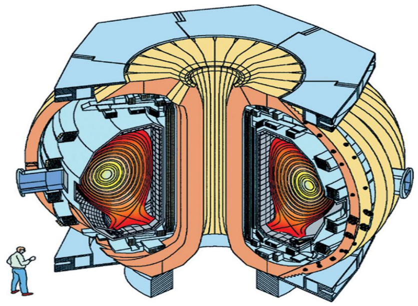
- ✓**Gyro-fluid extension**
- ✓**RMPs**
- ✓**Neutrals & impurities**
- ✓**Preconditioner**
- ✓**Massive concurrency**

2000 2005 2011

•**Umansky, Xu, Dudson, et al., , Comp. Phys. Comm. V. *180 , 887-903 (2008).***
Dudson, Umansky, Xu et al., Comp. Phys. Comm. V.180 (2009) 1467.
Xu, Dudson, Snyder et al., PRL 105, 175005 (2010).

BOUT and BOUT++ have been products of broad international collaborations





GENERAL ATOMICS

Argonne NATIONAL LABORATORY

ILLINOIS INSTITUTE OF TECHNOLOGY

THE UNIVERSITY of York

THE UNIVERSITY OF CALIFORNIA UCLA

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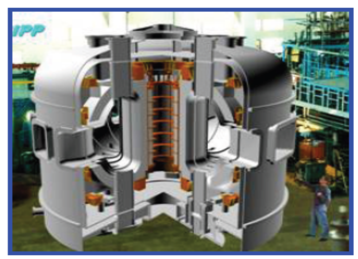


Institute of plasma Physics
Chinese Academy of Sciences

MIT PSFC

THE UNIVERSITY of WISCONSIN MADISON

ifts 浙江大學聚變理論與模擬中心 潘雲鶴

Institute for Fusion Theory and Simulation, Zhejiang University

北大聚变模拟中心

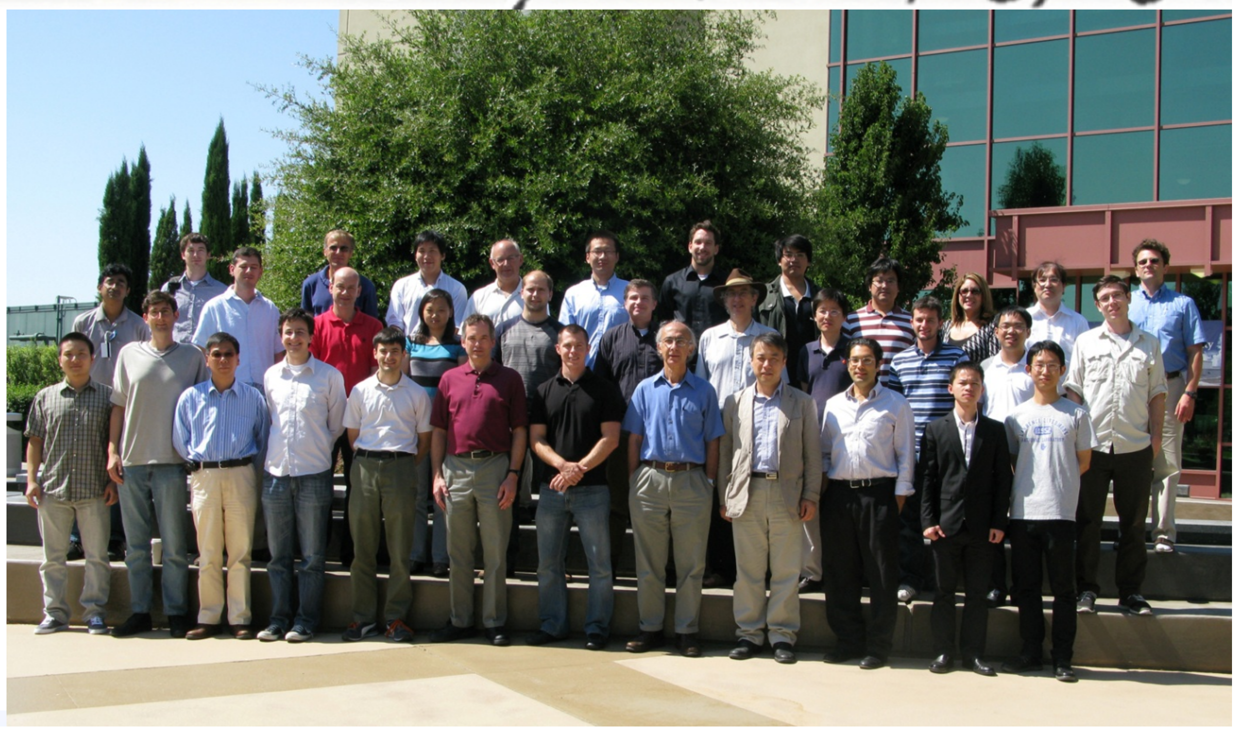
Fusion Simulation Center, Peking University

https://bout2011.llnl.gov

The workshop goals:

○ to prepare researchers to use and further develop the BOUT++ code for edge turbulence, transport, and ELM simulations of magnetic fusion devices; and

○ to promote effective collaboration within the BOUT community and beyond.



There are 45 workshop attendees from five countries: China, PRC (3), Japan (2), Korea, ROK (3), UK (2) and USA (35)

Special lectures on
- BOUT++ overview, status, code structures
- Solvers and numerical Schemes
- Gyro-fluid extensions

Hands-on examples
- Basic plasma instabilities
- Advanced example on ELM simulations
- BOUT++ applications to tokamaks & linear machines

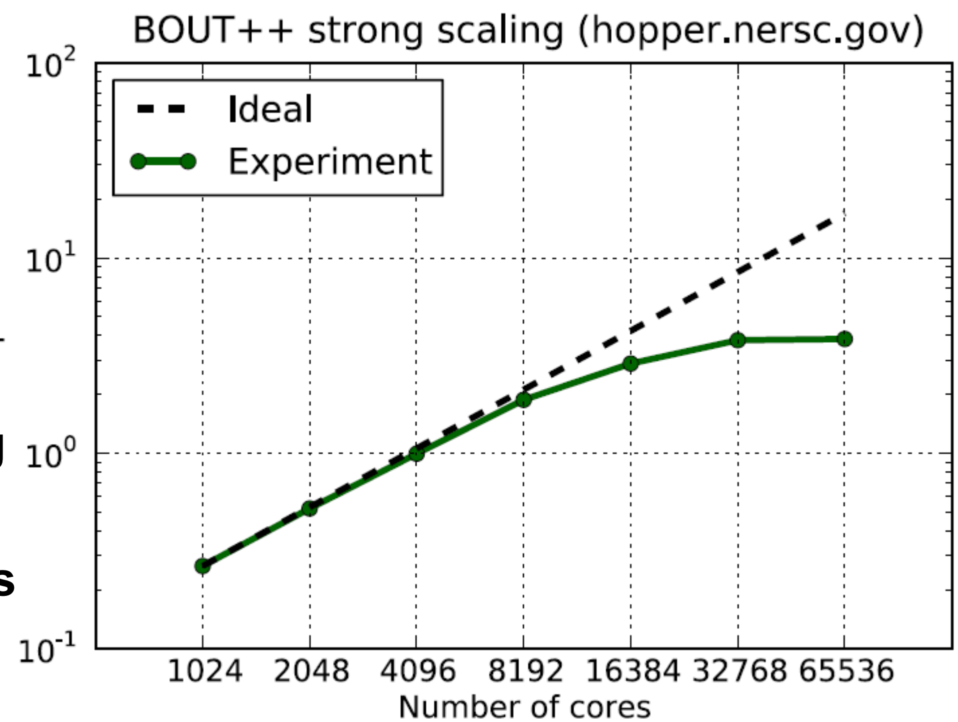
Lecture notes & hands-on examples are online

https://bout2011.llnl.gov

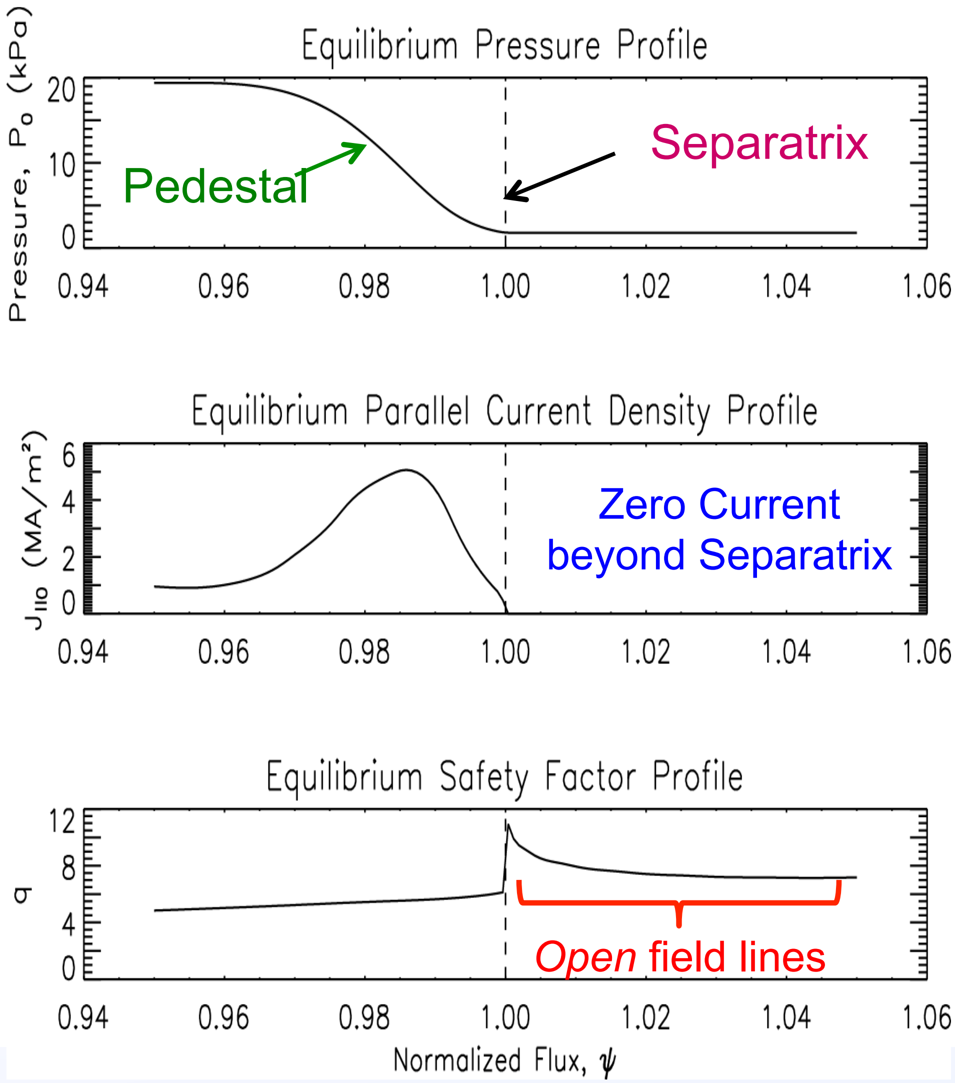
BOUT++ Code can be run at high concurrency

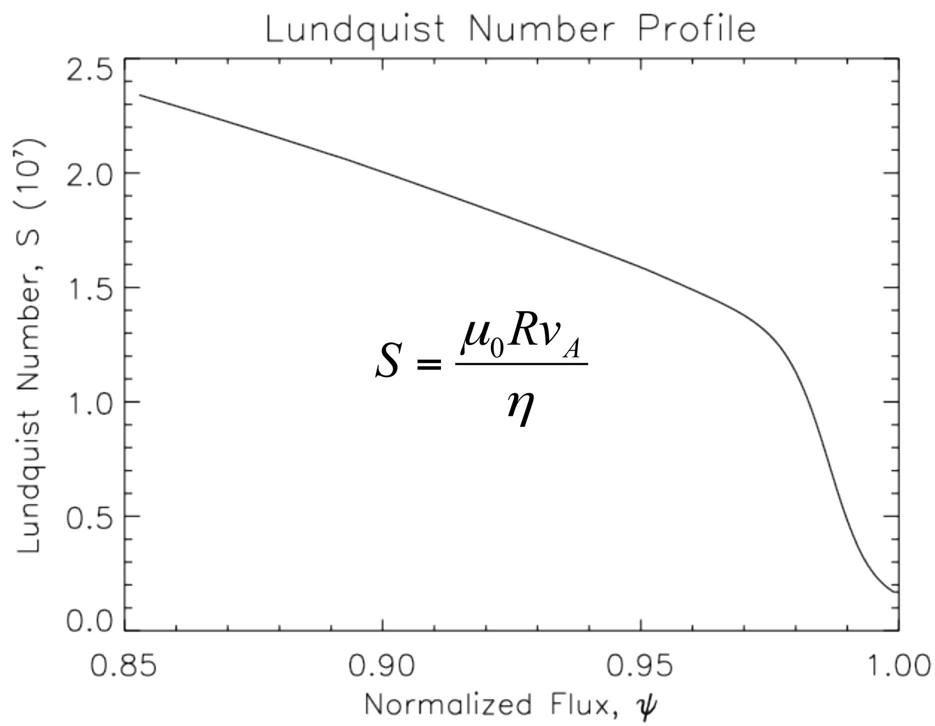
- Direct numerical simulation of plasma turbulence
  - Fluid equations based on Braginskii equations for N_i, T_e, T_i, $V_{||e}$, $V_{||i}$, and ϖ
  - Time integration by implicit ODE solver CVODE and PETSc
  - Parallel implementation with MPI
- BOUT++ provides an object-oriented framework in C++
  - Modular!!!
- MPI parallelization allows ideal strong scaling to hold up to *10,000* cores!
- Multi-developer version control allows for efficient development

P Narayanan et al. Performance Characterization for Fusion Co-design Applications". In: Proceedings of CUG (2011).



C-Mod Equilibrium EDA H-Mode Parameters used as BOUT++ Input (1110201023.00900)

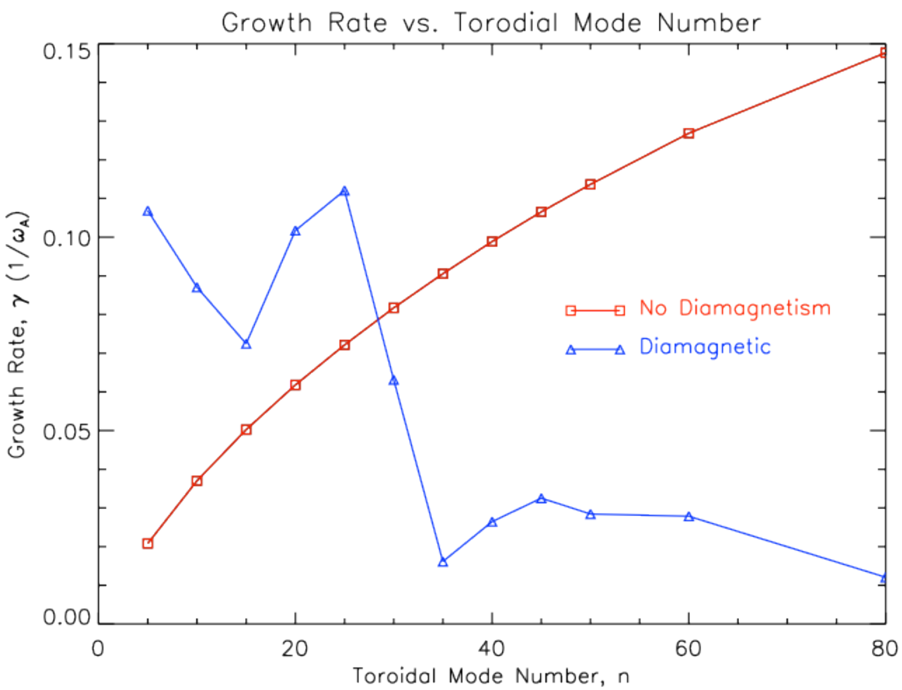


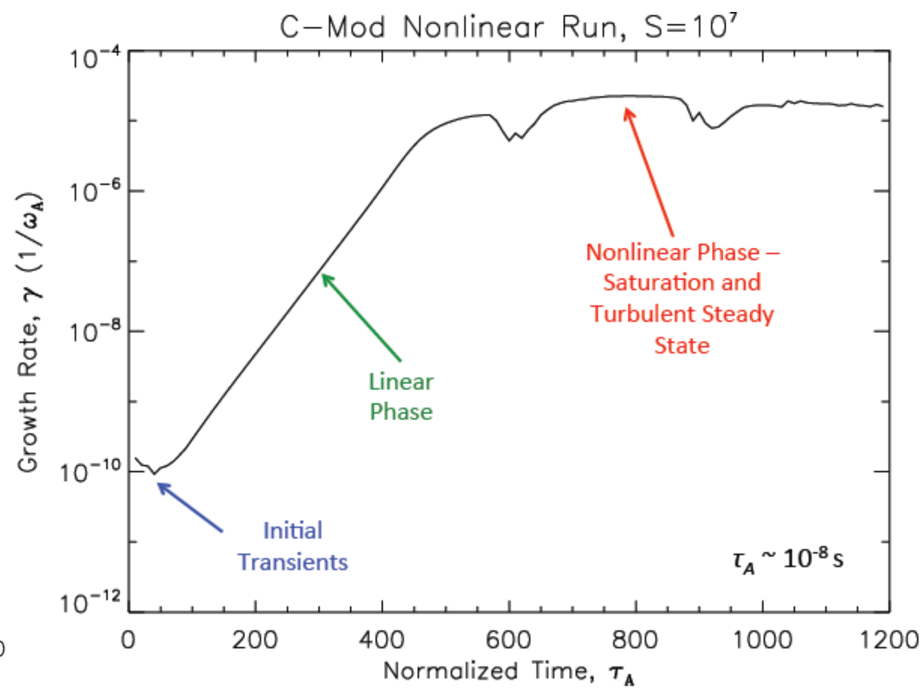


Lundquist Number (*S*) is a dimensionless ratio of the resistive diffusion time to the Alfvén time

- ***S*** **~10^7** in C-Mod EDA pedestal

BOUT++ Calculations Show C-Mod EDA H-Modes Resistively Unstable

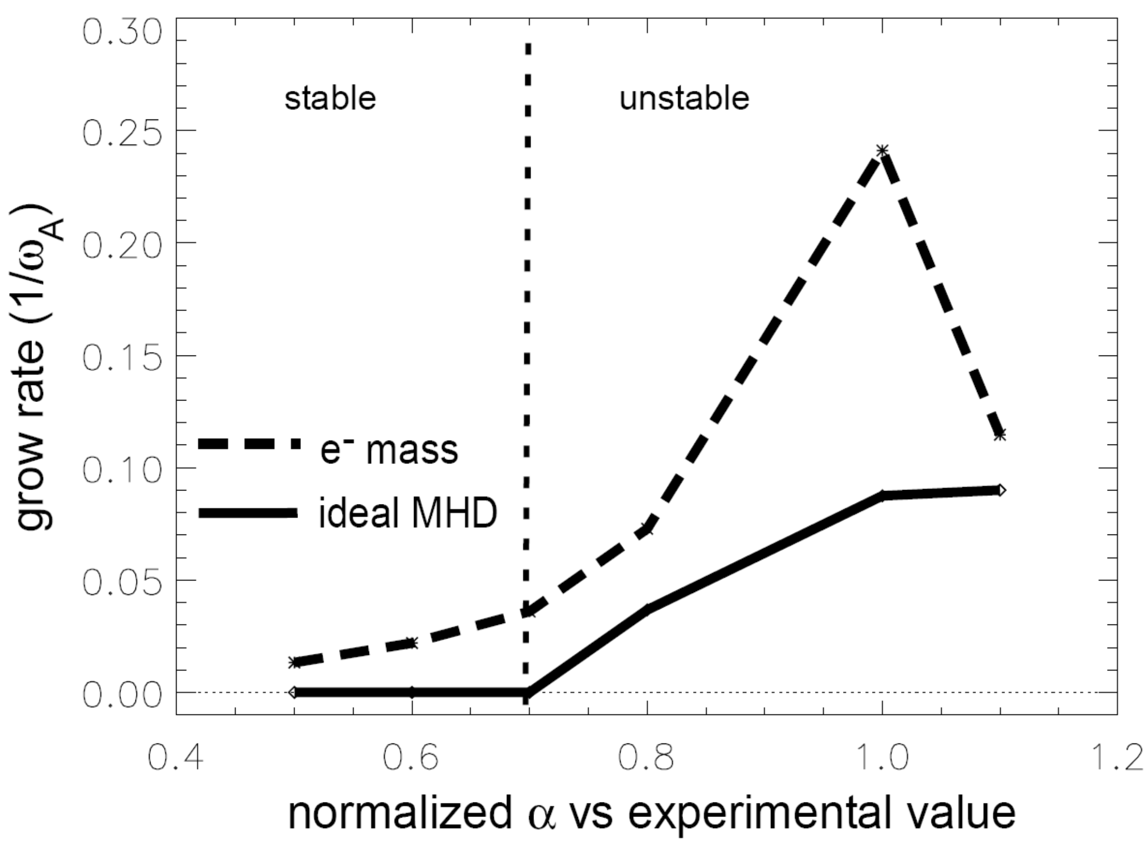


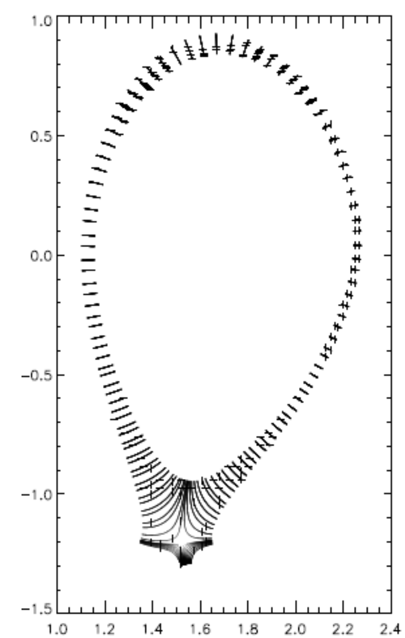


BOUT++ calculations show that Diamagnetic Effects Damp Higher Mode Numbers, yielding the growth rate peaks at n=25, consistent with measurements.

Preliminary Nonlinear Simulations have begun --- Mode Saturation and Turbulent Steady-State have been Observed. Comparisons with experimental measurements will begin.

BOUT++ simulations for DIII-D ELMy H-mode shot #131997 at reduced $J_{||}$





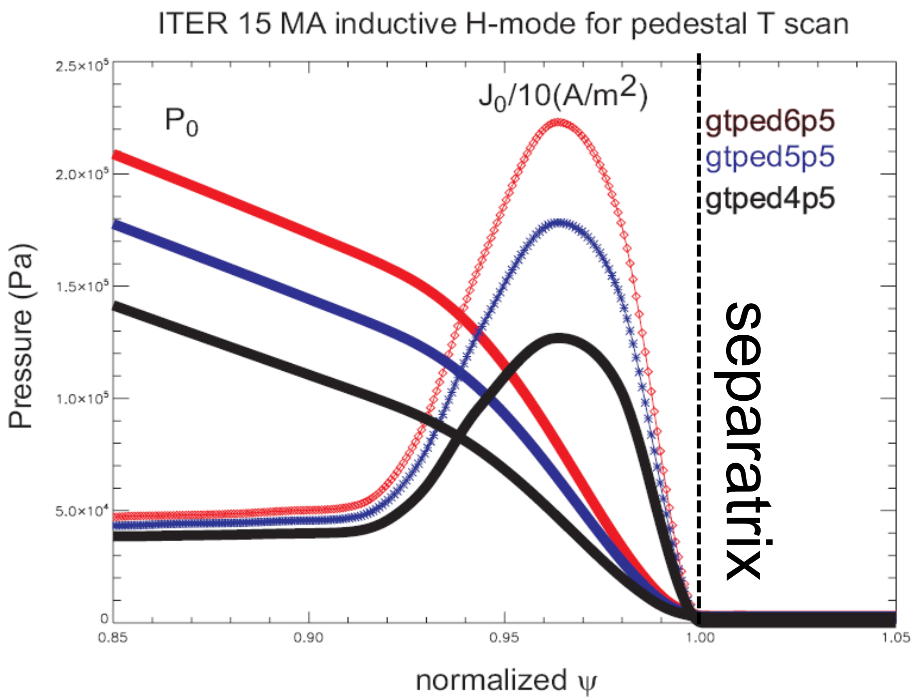
✓Ideal MHD stability boundary is consistent with infinite-n BALLOO code

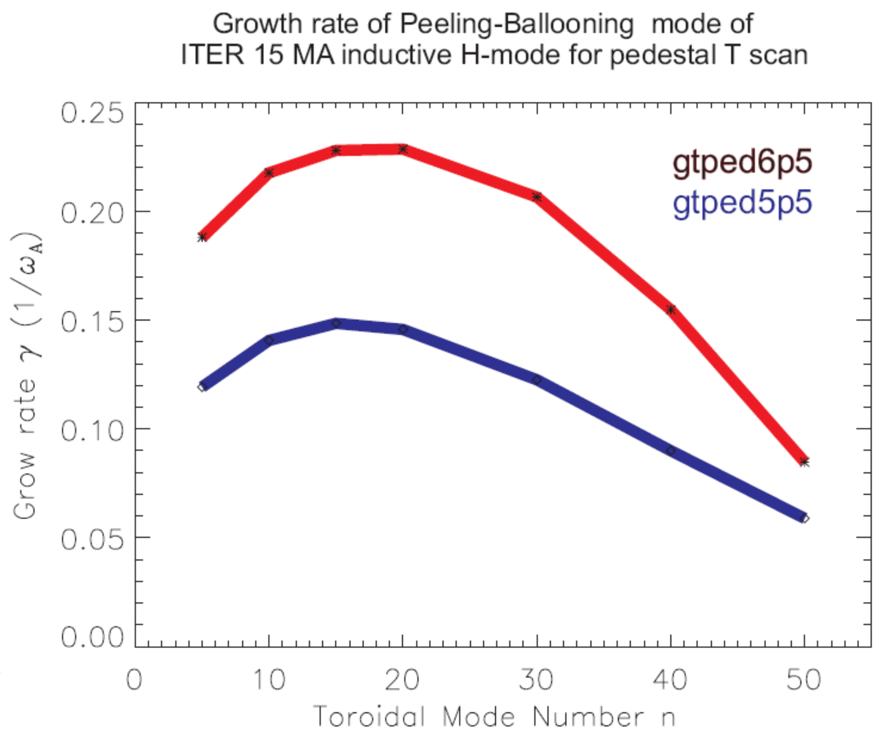
✓Inclusion of e^- inertial eliminates the stability boundary

BOUT++ simulations for one of the latest designs of the ITER 15 MA inductive ELMy H-mode scenario (under the burning condition)

- Simulations starting from equilibrium generated by the CORSICA code.

china eu india japan korea russia usa





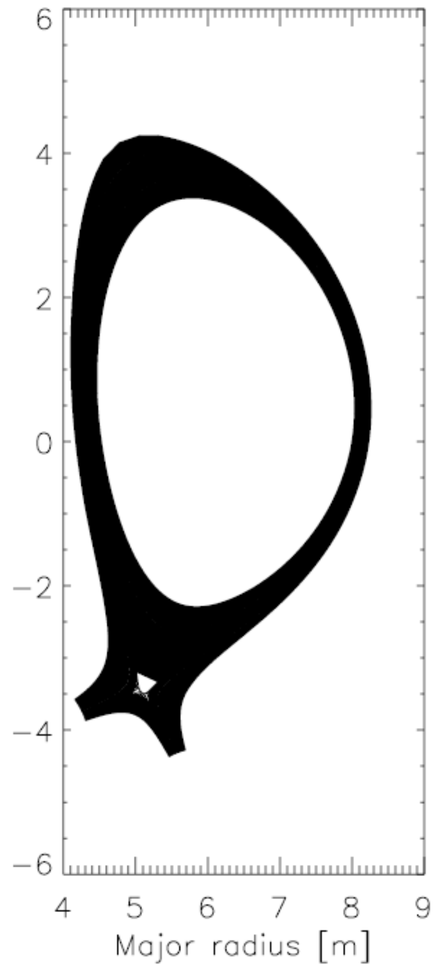
- Marginal unstable pedestal case, T_{ped}=5.5keV, n_{max}=15
- The calculations impact previous ITER ELMy H-mode scenario design as it was based on the pedestal height T_{ped}=4keV

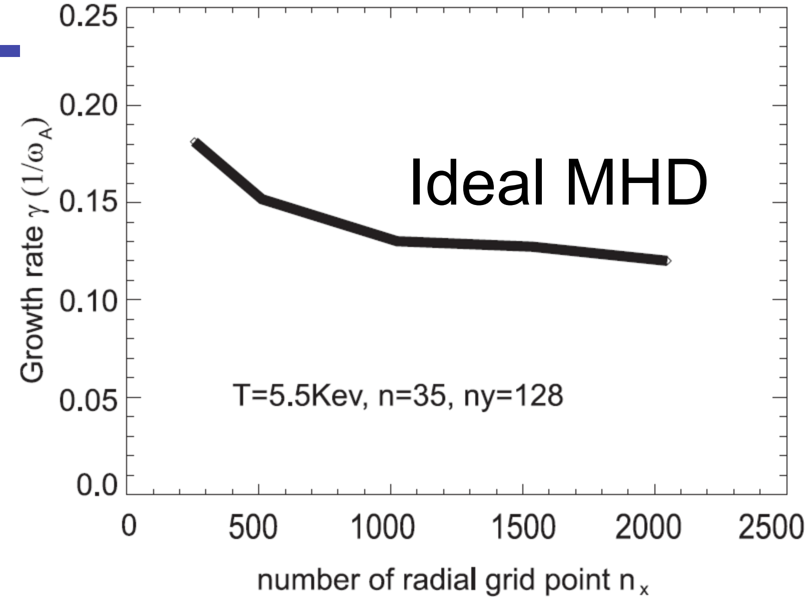
Fusion Energy Sciences

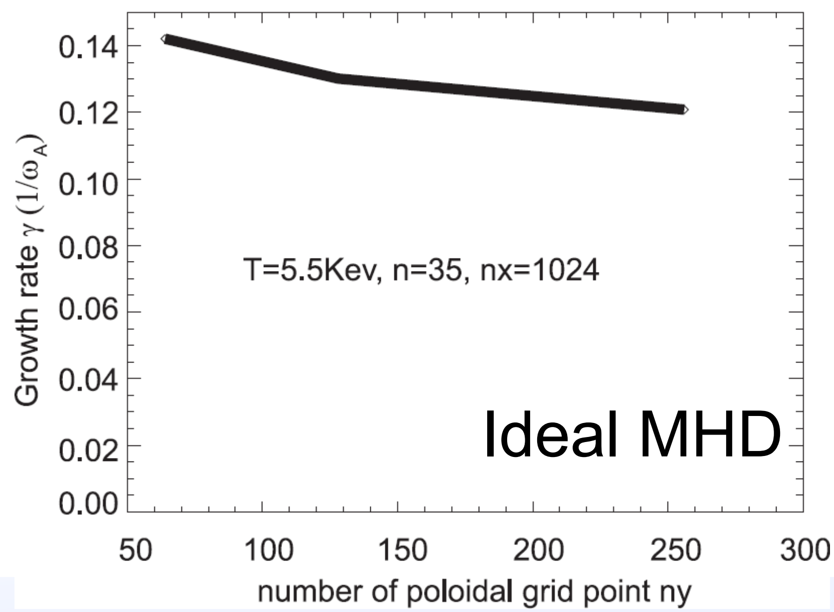
X.Q.Xu, B.D.Dudson, P.B.Snyder, M.V.Umansky, H.R.Wilson and T.Casper, Nucl. Fusion 51 (2011)

BOUT++ simulations for one of the latest designs of the ITER 15 MA inductive ELMy H-mode scenario

It is numerical challenge to simulation ITER divertor geometry, requiring high resolutions nx > 1000, ny>100, even for linear mode.







china eu india japan korea russia usa

X.Q.Xu, B.D.Dudson, P.B.Snyder, M.V.Umansky, H.R.Wilson and T.Casper, Nucl. Fusion 51 (2011)

BOUT++ simulations show radial and poloidal mode structures and for the ITER 15 MA inductive ELMy H-mode scenario

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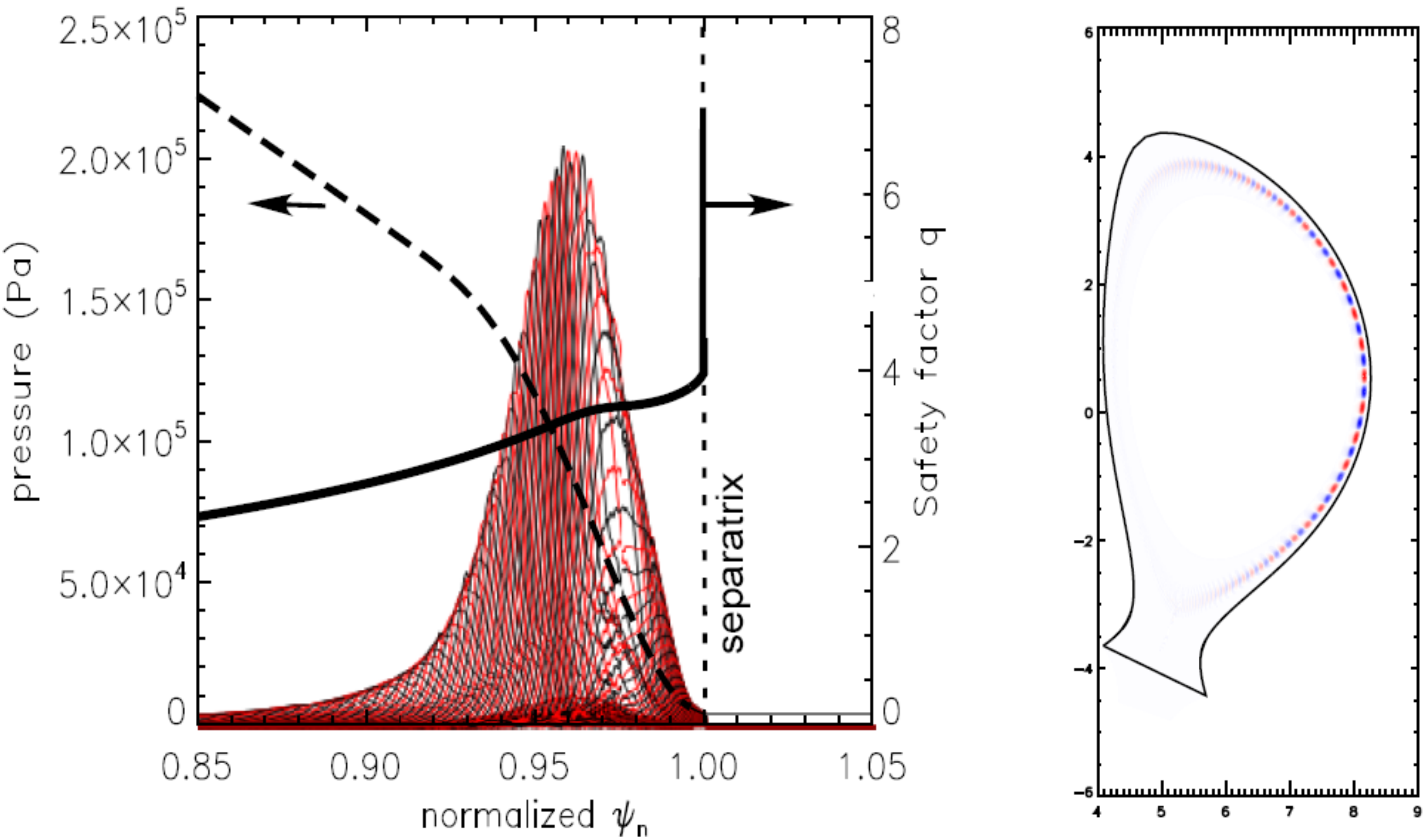

Fusion Energy Sciences

X.Q.Xu, B.D.Dudson, P.B.Snyder, M.V.Umansky, H.R.Wilson and T.Casper, Nucl. Fusion 51 (2011)

Nonlinear simulations of peeling-ballooning modes with anomalous electron viscosity in ELM crashes

The Nonlinear System of Equations for Simulating Non-Ideal MHD Peeling-Ballooning Modes

Reduced MHD Equations

Vorticity

$$\frac{\partial \varpi}{\partial t} + v_E \cdot \nabla \varpi = B_0^2 \nabla_\parallel \left(\frac{j_\parallel}{B_0} \right) + 2 b_0 \times \kappa \cdot \nabla p,$$

Pressure

$$\frac{\partial P}{\partial t} + v_E \cdot \nabla P = 0,$$

Ohm's

$$\frac{\partial A_\parallel}{\partial t} = -\nabla_\parallel \left(\phi + \Phi_0 \right) + \frac{\eta}{\mu_0} \nabla_\perp^2 A_\parallel - \frac{\eta_H}{\mu_0} \nabla_\perp^4 A_\parallel,$$

Definitions

$$\varpi = \frac{n_0 M_i}{B_0} \left(\nabla_\perp^2 \phi + \frac{1}{n_0 Z_i e} \nabla_\perp^2 p_i \right), \quad P = P_0 + p$$

$$j_\parallel = J_{\parallel 0} - \frac{1}{\mu_0} \nabla_\perp^2 A_\parallel, \quad v_E = \frac{1}{B_0} b_0 \times \nabla \left(\phi + \Phi_0 \right)$$

Non-ideal physics

✓Using resistive MHD term, resistivity can be renormalized as **Lundquist** Number

$$S = \mu_0 R v_A / \eta$$

✓Using hyper-resistivity η_H

$$S_H = \mu_0 R^3 v_A / \eta_H = S / \alpha_H$$

✓After gyroviscous cancellation, the diamagnetic drift modifies the vorticity and additional nonlinear terms

✓Using force balance and assuming no net rotation,

$$E_{r0} = (1/N_i Z_i e) \nabla_\perp P_{i0}$$

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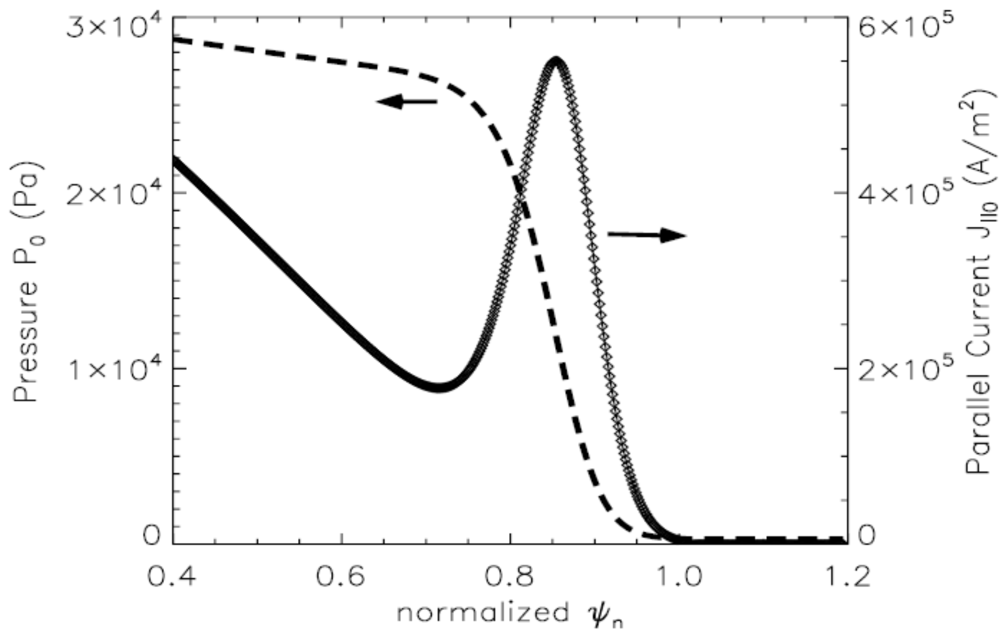
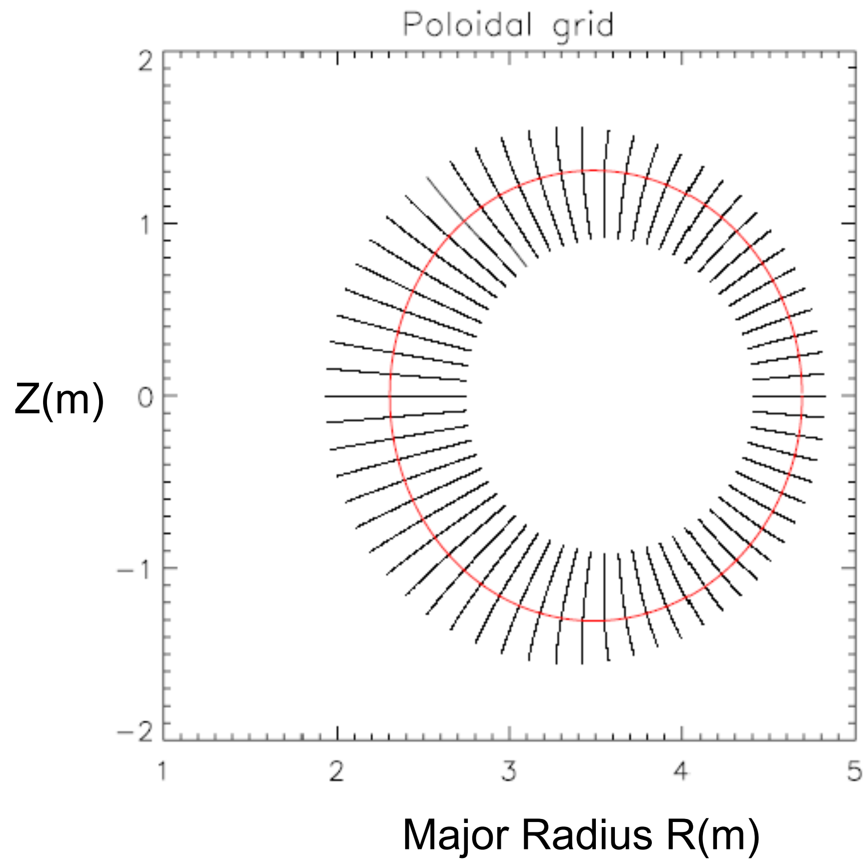
Equilibrium current and pressure profiles.





Perturbed pressure Contours from Nonlinear P-B modes

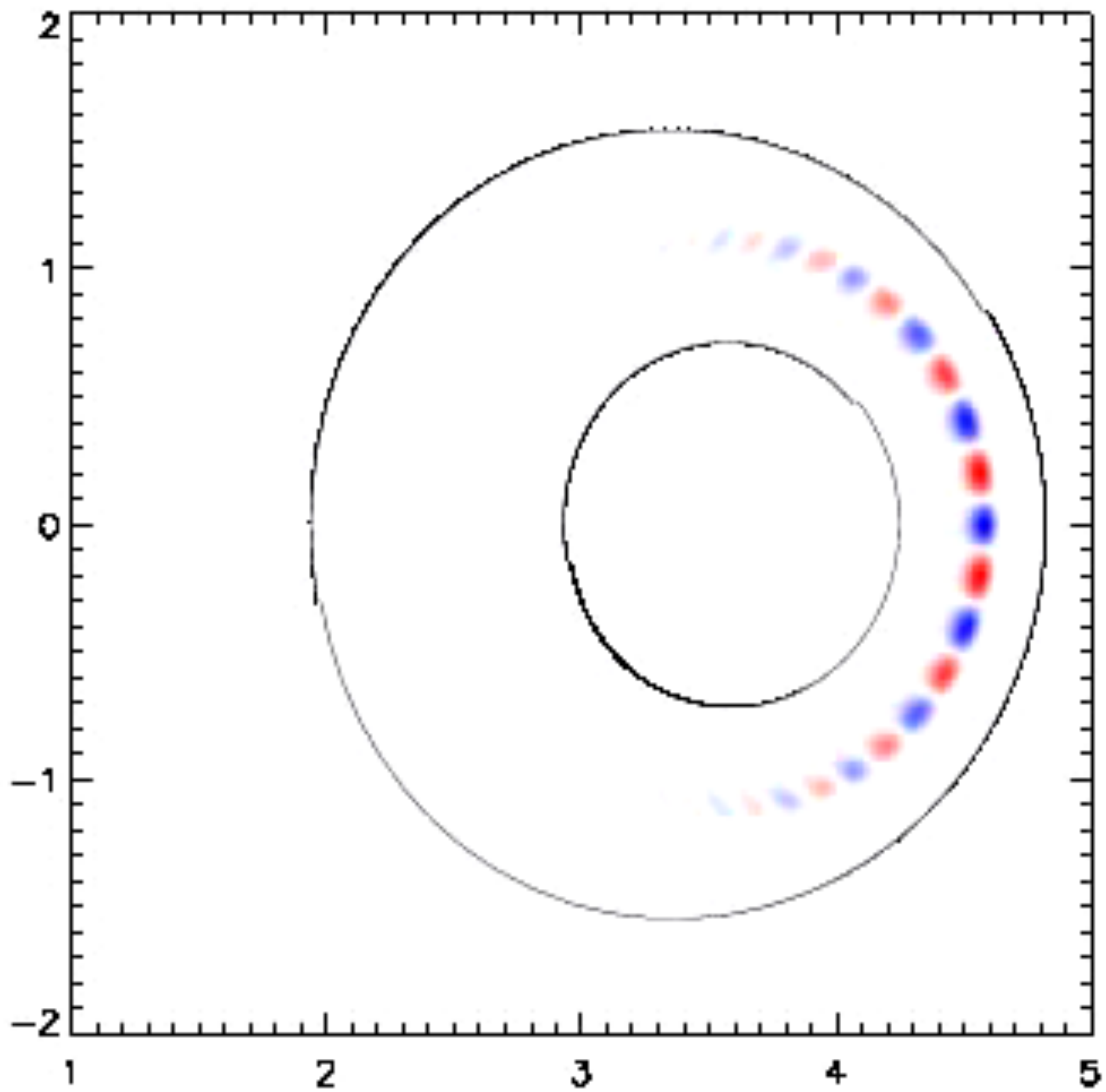
512x64x64,

$S=10^8$ & $S_H=10^{12}$

Pressure fluctuation

$2\mu_0\delta p/B^2$

contours-- poloidal cross section



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Pressure Profile from BOUT++ Nonlinear P-B modes

512x64x64,

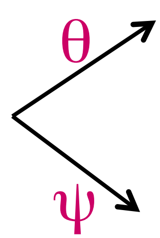
$S=10^8, S_H=10^{12}$

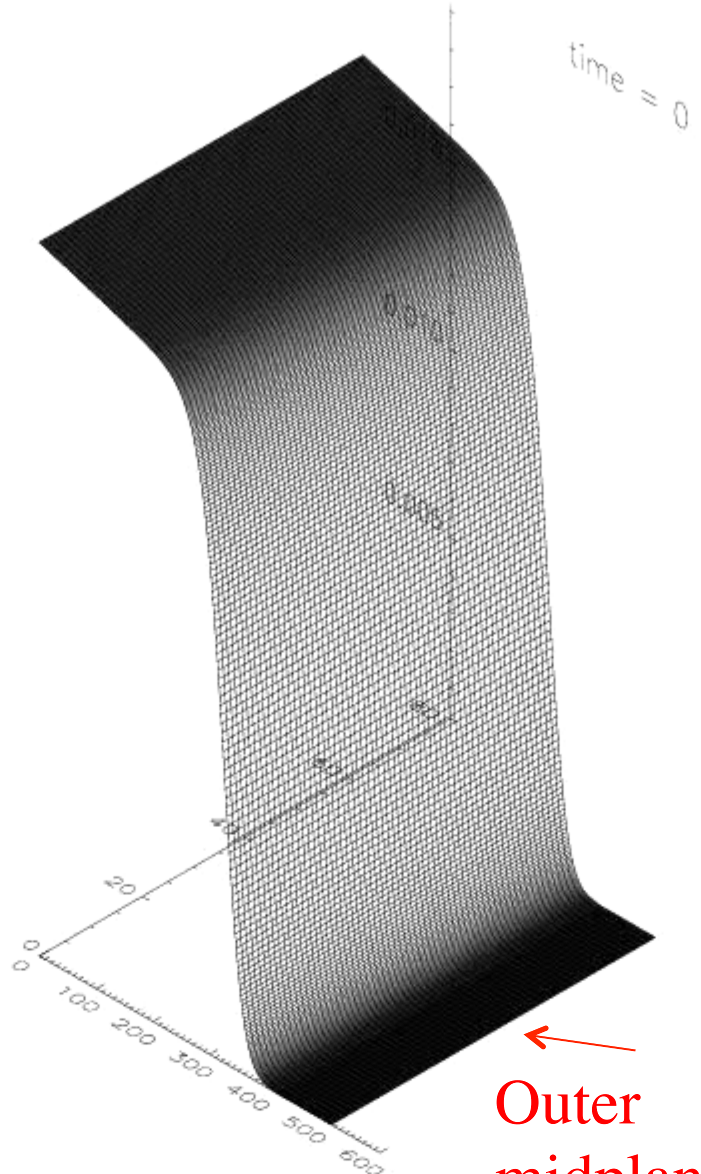
Pressure profile:

$2\mu_0\langle P\rangle/B^2$ $\quad P=P_0+\langle\delta p\rangle$

pressure vs. radius and

poloidal angle





Outer midplane

Perturbed pressure Contours from nonlinear P-B modes

512x64x64,

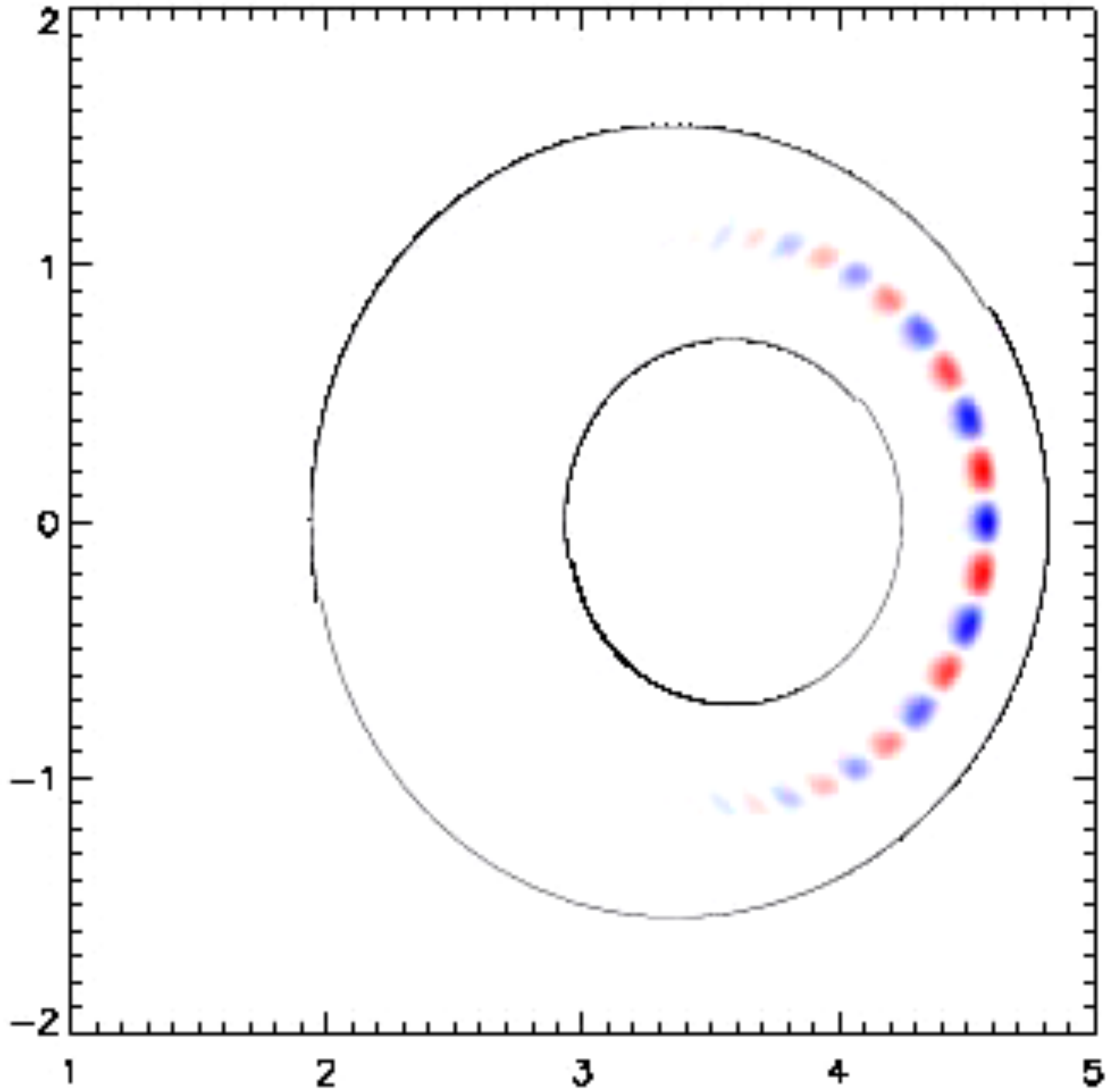
$S=10^5$ & $S_H=10^{12}$

Pressure fluctuation

$2\mu_0\delta P/B^2$

contours-- poloidal

cross section



Pressure Profile from Nonlinear P-B modes

512x64x64,

$S=10^5$ & $S_H=10^{12}$

Pressure profile:

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pressure vs. radius and

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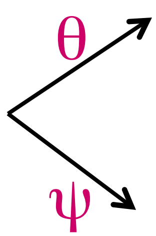
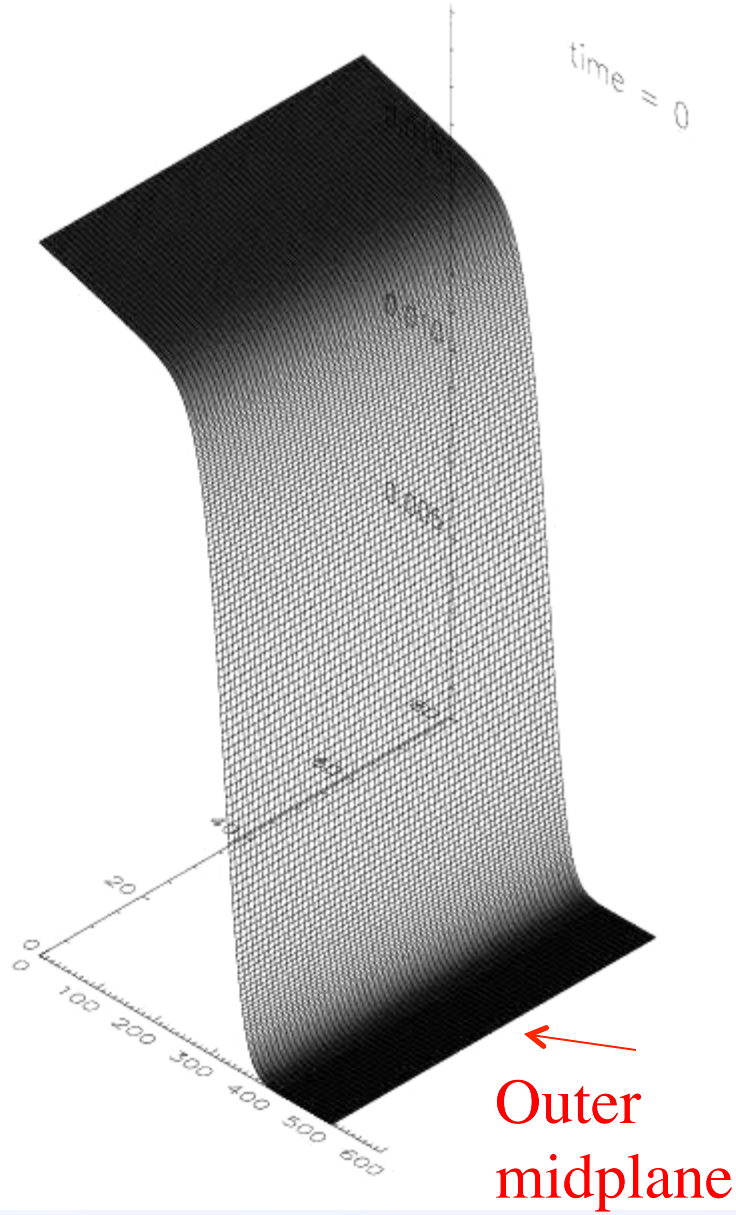
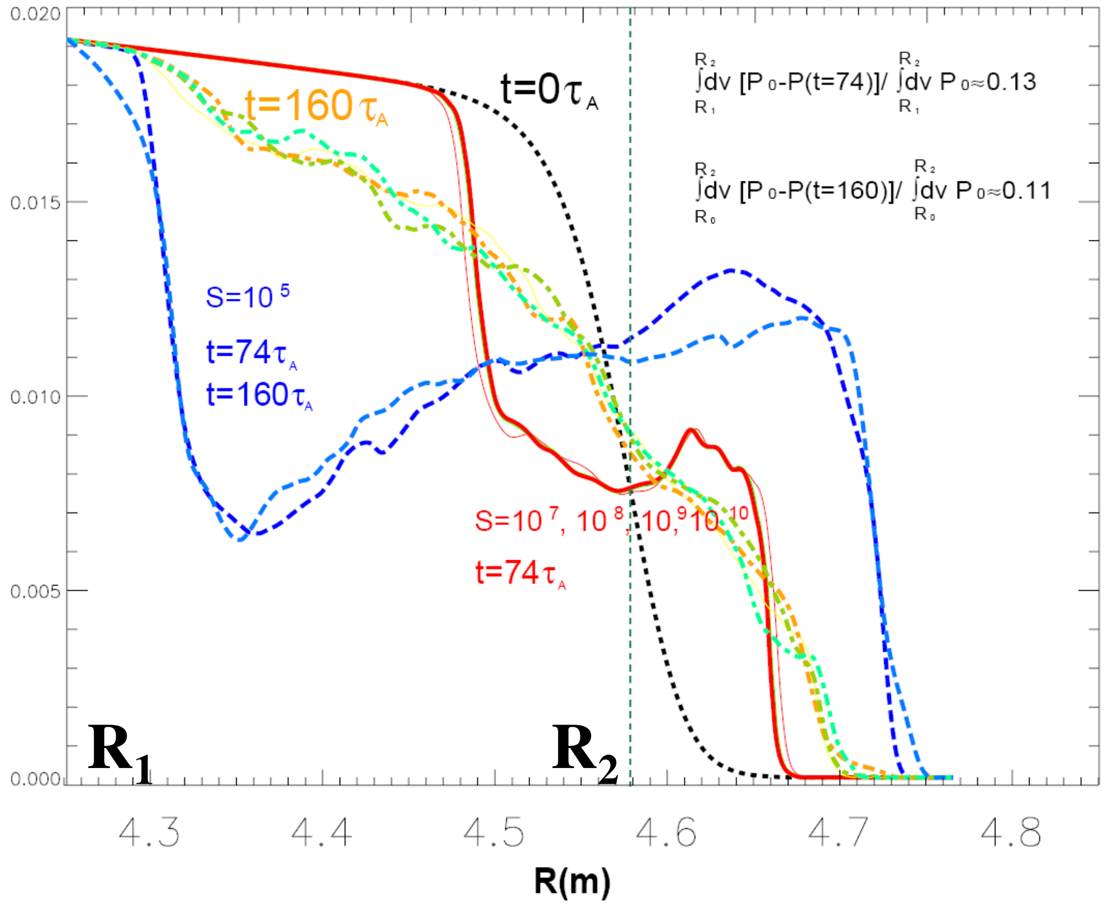




Flux-surface-averaged pressure profile $2\mu_0 \langle P\rangle/B^2$ vs S with $S_H=10^{12}$

low S -> large ELM size, ELM size is insensitive when $S>10^7$



$\int_{R_1}^{R_2} dv\,[P_0-P(t=74)] / \int_{R_1}^{R_2} dv\,P_0 \approx 0.13$

$\int_{R_0}^{R_2} dv\,[P_0-P(t=160)] / \int_{R_0}^{R_2} dv\,P_0 \approx 0.11$

ELM size= $\Delta W_{ped}/ W_{ped}$

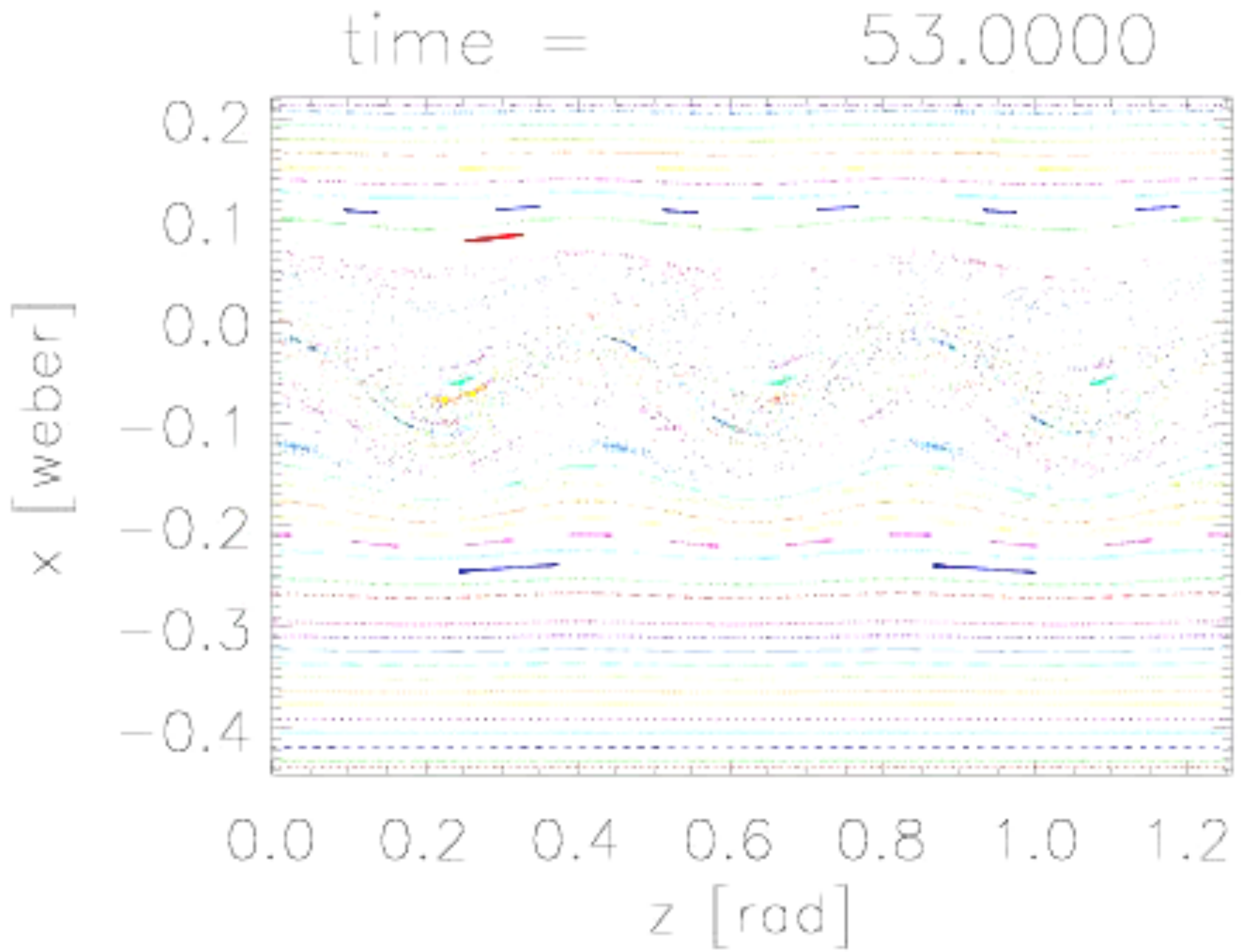
ΔW_{ped}= the ELM energy loss

W_{ped} =pedestal stored energy

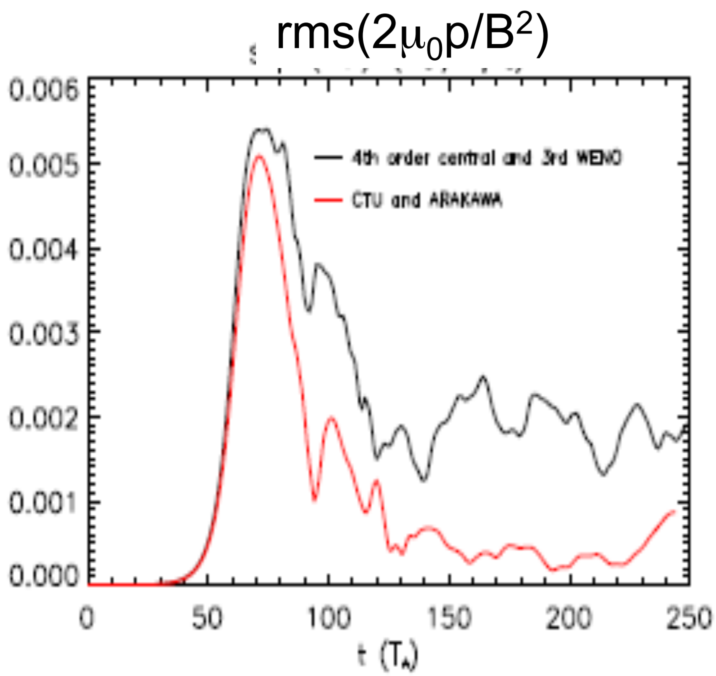
(1) a sudden collapse: P-B modes -> magnetic reconnection -> bursting process

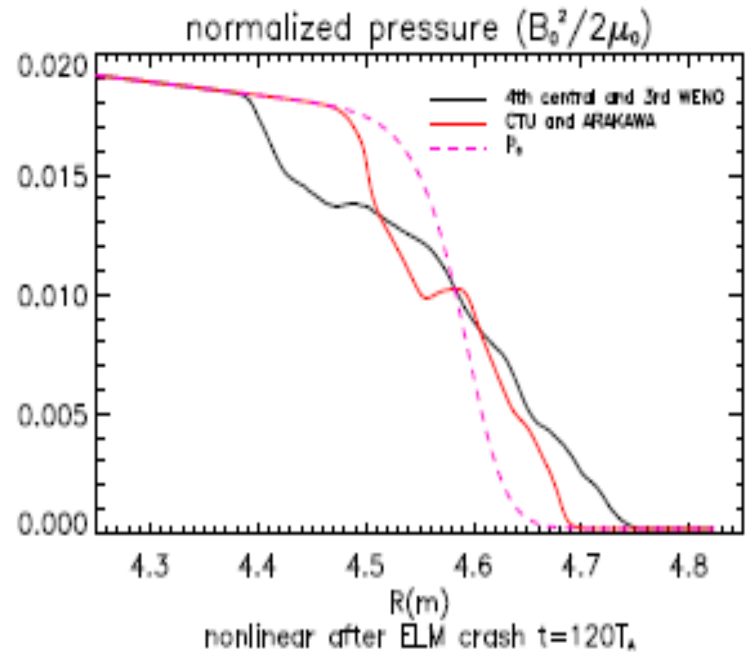
(2) a slow backfill as a turbulence transport process

For lower S (10^6), the reconnection region grows and the pedestal collapse becomes much larger.



Higher order differencing scheme is essential for ELM & turbulence simulations





- **The lower order differencing method results in smaller growth rate and much smaller saturate pressure perturbation.**
- **Lower order method reduces ELM size by more than 50%.**

P2-1 T. Xia, X. Xu, B. Dudson, and J. Li,
Nonlinear Simulations of Peeling-Ballooning Modes with Flow Shear and RF Sources, Wednesday afternoon